CLARREO sampling studies

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Approach

- CLARREO focus is to detect climate trends in the inter-annual TOA flux variability spanning decadal time scales over large spatial scales
  - Minimum benchmark requirement is the 10° zonal annual anomaly
  - Also be looking at finer temporal and spatial scales
- The time period to detect a significant trend depends on
  - Magnitude of the natural variability: ENSO, seasonal, diurnal, semi-diurnal, are natural oscillations
  - Magnitude of the trend
  - Calibration error
  - Sampling error
- Design orbit to minimize sampling error and track expected climate signals
  - Design orbits to decrease sampling errors and to observe predicted climate changes, for example polar regions and diurnal surface temperatures
  - Single P90 has the advantage of seeing the poles and processing through seasonal and diurnal cycles and can can inter-calibrate other SS satellites
  - The SS13:30 orbit is a historical operational SS orbit and for the future JPSS missions

Trend detection

- Time it takes to detect a signal above natural variability, with a signal to noise ratio of s

Leroy, J Climate 2008

Natural variability term

Measurement error term

$$\Delta t = \{[12 s^2 / m_{est}^2]\sigma_{var}^2 \tau_{var}^2\} F_t$$

$$F_t = (1 + \sum f_i^2)^{1/3}$$

F_t is the factor that predicts the deviation from a perfect observing system
F =1 for perfect system, and F>1 for observing errors in sampling, calibration, etc.

$$f_i^2 = (\sigma_i^2 \tau_i) / (\sigma_{var}^2 \tau_{var})$$

Measurement error is expressed as a ratio between measurement error and natural variability

$$\sigma_i / \sigma_{var} = \sqrt{[F_t^3 - 1][\tau_{var} / \tau_i]}$$

Sampling error/natural variability

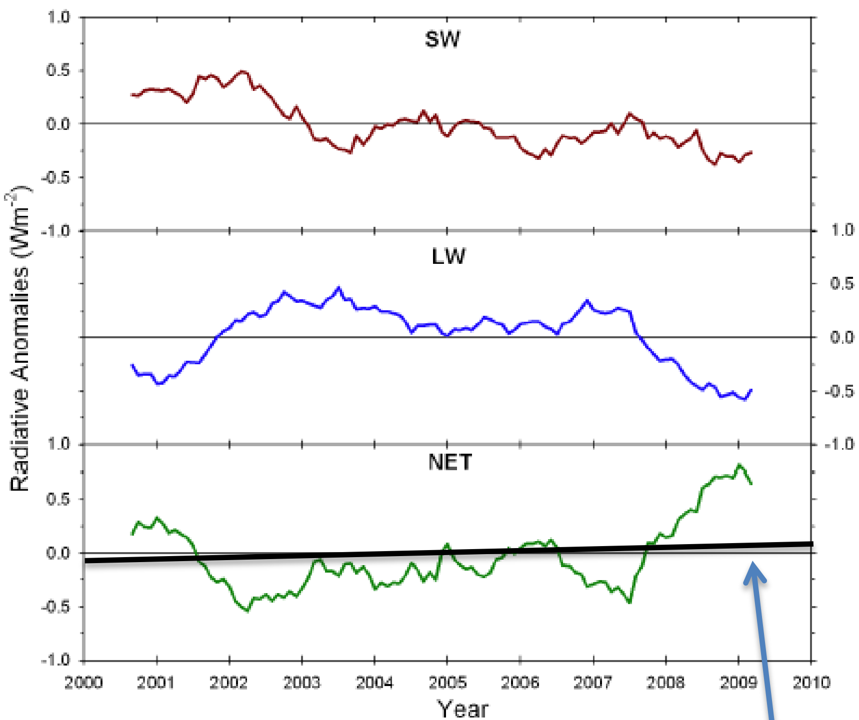
- Use Leroy τ_{var} = 1.5 years and τ_i = 1.0 years for annual anomaly studies
- If you allow sampling error to be 10% greater than the perfect observing system, then F_t = 1.1 and (σ_i/σ_{var}) = 0.70

F_t	1.02	1.05	1.10	1.20	1.50	2.00
σ_i/σ_{var}(%)	30	50	70	104	190	324

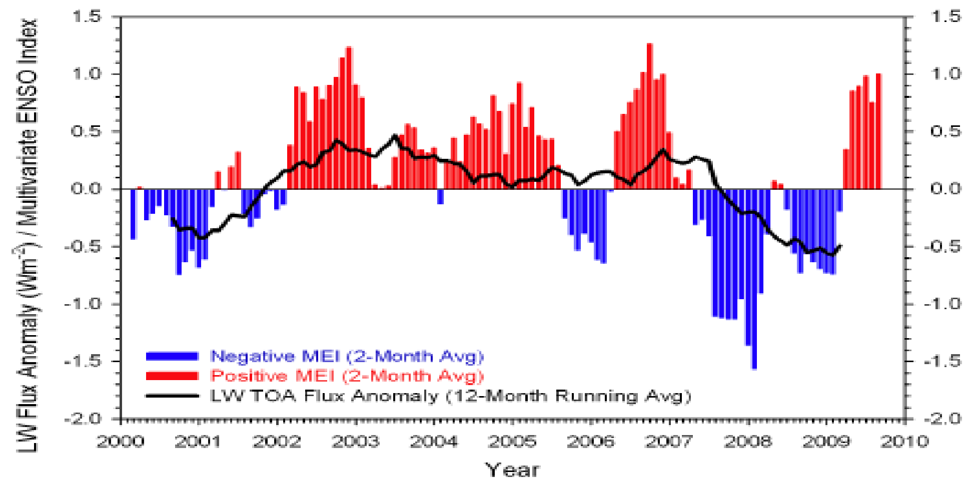
CERES 10 year flux anomalies

(natural variability)

Deseasonalized 12 month running flux means

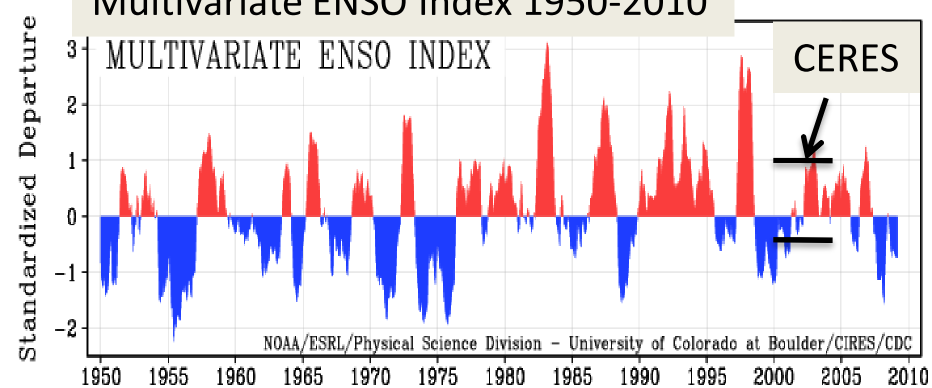


LW flux anomaly with ENSO Index



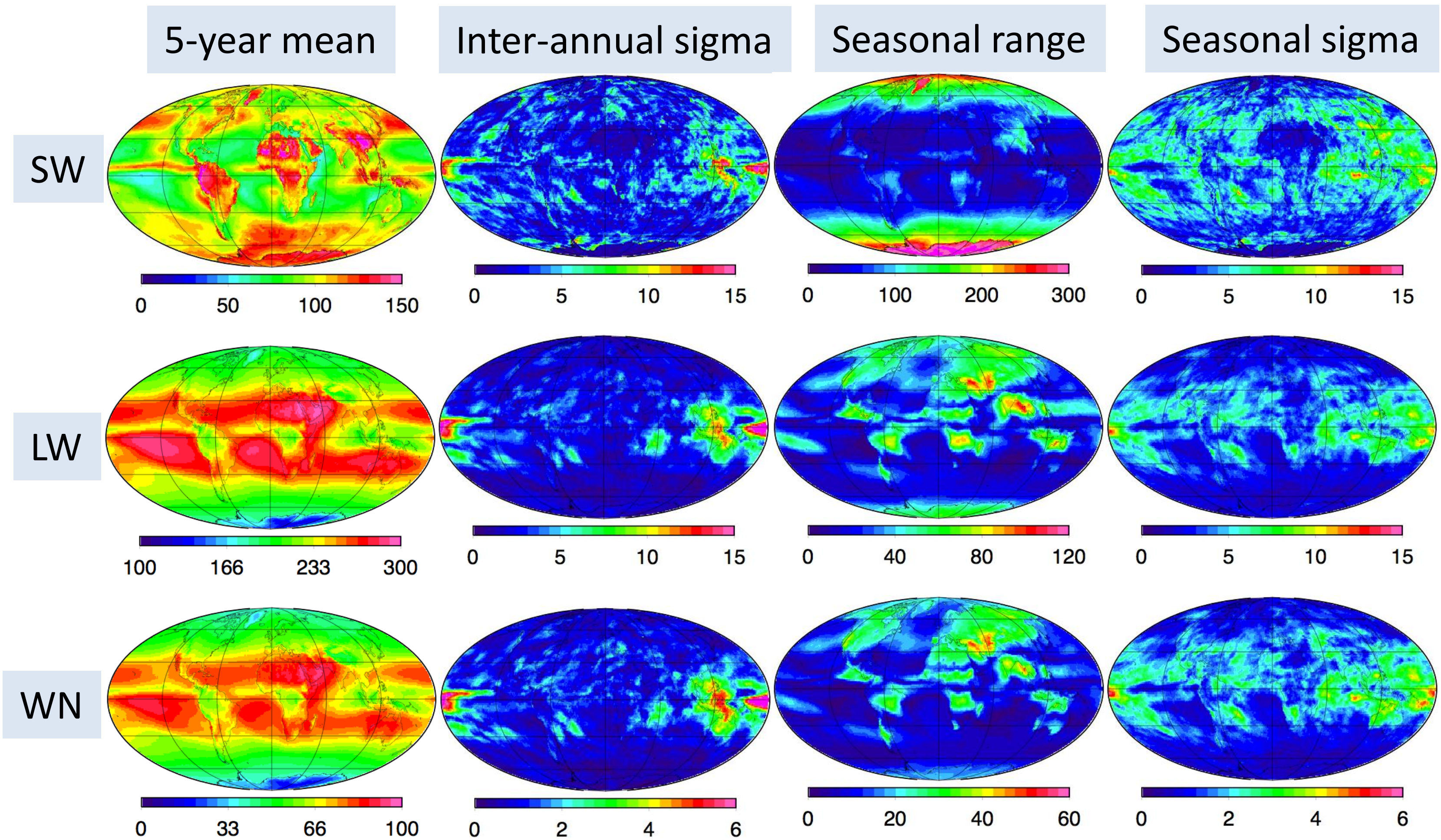
- 0.3Wm-2/decade (50% of IPCC predicted forcing)
- 14 years to detect predicted forcing, at the 95% significance level with a probability of 90%

Multivariate ENSO Index 1950-2010

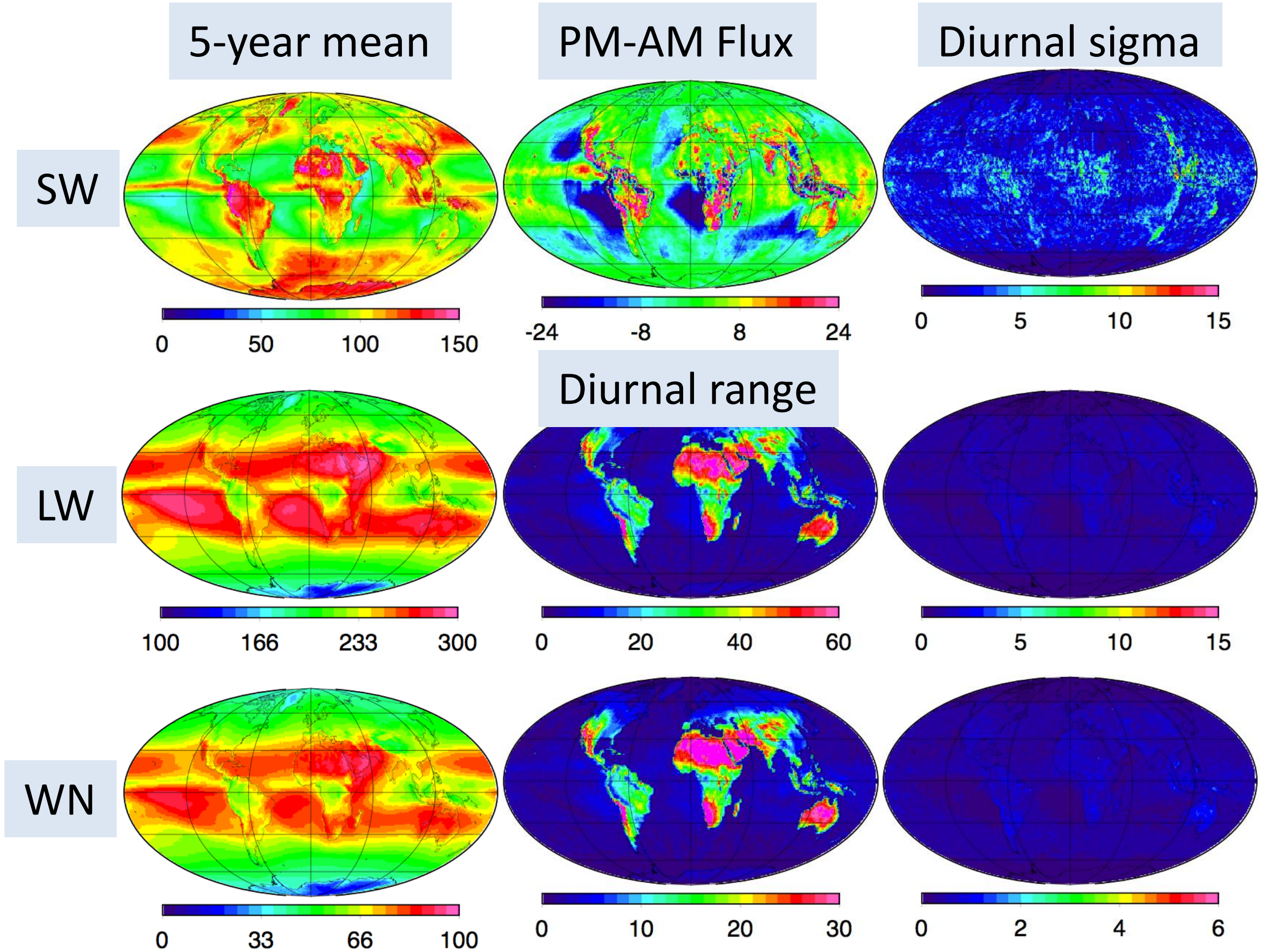


CERES data within low ENSO variability

Inter-annual and seasonal cycles and variability



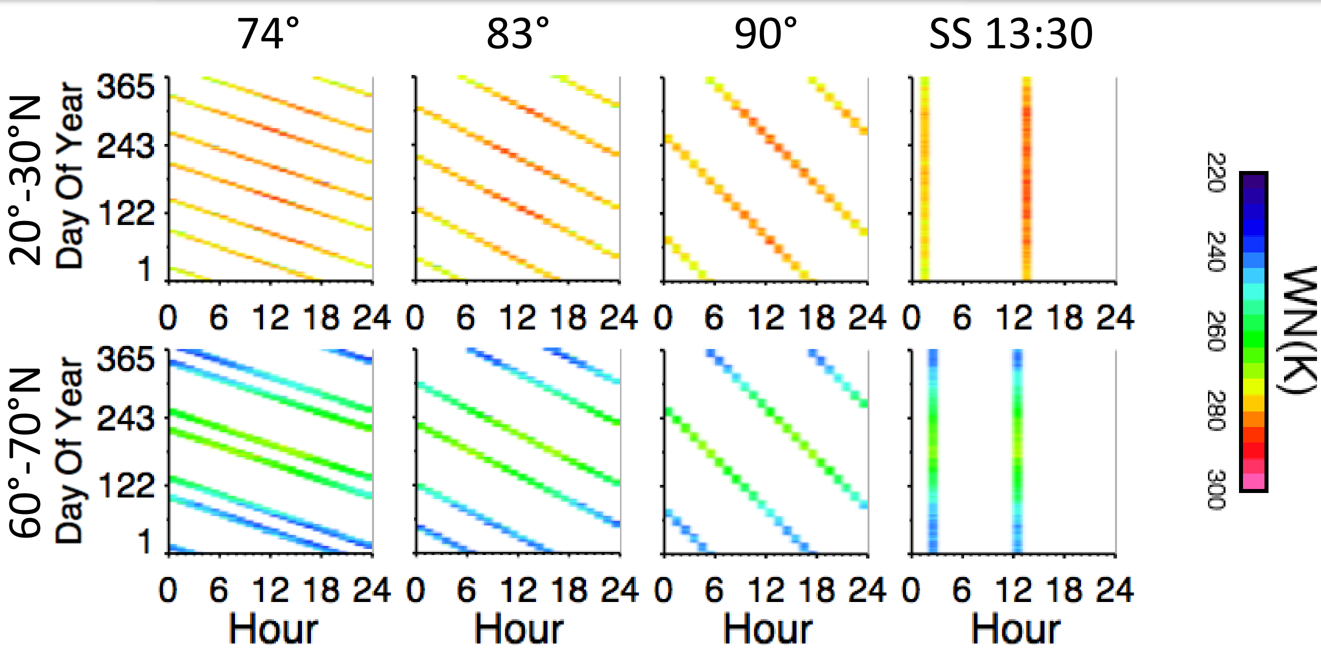
Diurnal cycles and variability



- Inter-annual variability due to ENSO is larger than seasonal or diurnal variability
- However the diurnal and seasonal cycles are very large
- Satellite sampling needs to detect the variability while observing large seasonal and diurnal oscillations

CLARREO Examined Orbits

Orbit	74°	83°	90°	98° (SS)
Diurnal cycles/year	6	4	2	0
Comments	92.5% coverage	98.5% coverage	Global coverage	A-train, JPSS No diurnal coverage



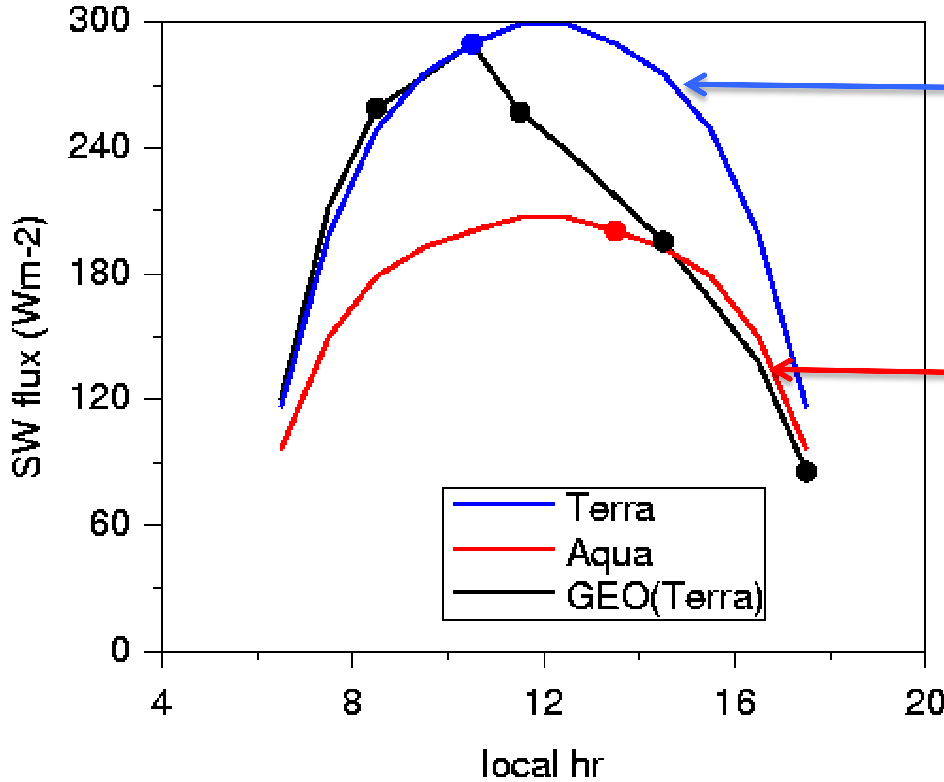
• The inclination of the precessionary orbit determines the number of seasonal cycles sampled through out the year
• The precessionary orbit allows sampling the diurnal cycle

CERES (natural variability) SW radiance dataset

- Use 5 years of (2001-2005) of hourly 1° (110km^2) gridded broadband SW fluxes from the CERES Terra SRBAVG-GEO dataset
  - CERES observes WN (8-12μm), LW broadband, SW broadband
  - Merged CERES Terra and 3-hourly 5-satellite GEO derived broadband fluxes
  - The GEO fluxes have been carefully normalized to the CERES fluxes to maintain CERES calibration
  - Temporally interpolate all measured fluxes to fill in all hourly increments
  - CLARREO measures radiances: need to convert fluxes into radiances
- Convert all the regional hourly SW fluxes to nadir radiance using CERES angular directional models (ADMs) based on over 600 scene types based on cloud and geo-type
  - All solar zenith angles (SZA)<90° are used
- Average all SW radiances into 10° zones for each of the dataset years

The merged CERES/GEO SW diurnal flux

- Peruvian maritime stratus region example, where morning stratus clouds that burn off in the afternoon, expect greater SW flux in the morning than afternoon



Terra SW hourly flux (ERBE temporal interpolation) which assumes constant meteorology at the 10:30 LT measurement time

Aqua SW hourly flux (ERBE temporal interpolation) which assumes constant meteorology at the 13:30 LT measurement time

Terra CERES 10:30 LT & 3-hourly GEO SW hourly flux (GEO temporal interpolation)

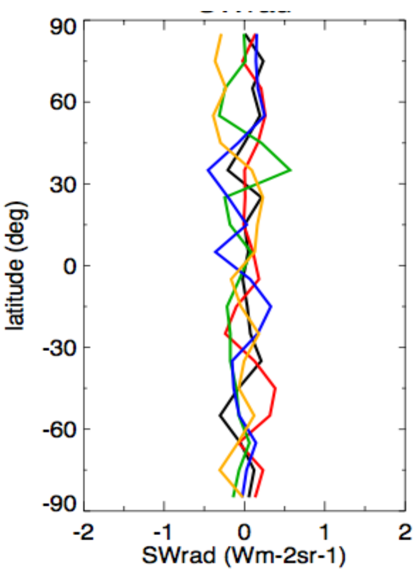
- The Terra 10:30 and Aqua 13:30 cannot replicate diurnal coverage
- Use Geostationary derived fluxes to complete diurnal coverage

Sampling strategy

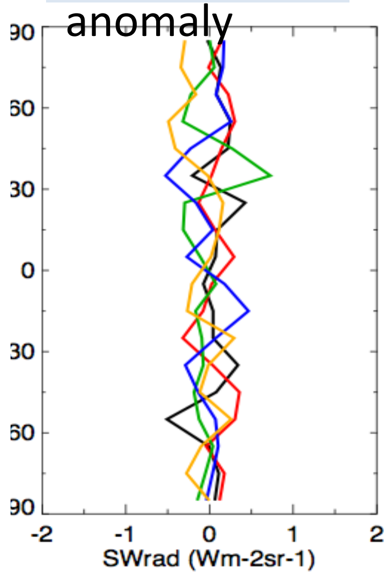
- Generate predicted CLARREO satellite ground-track files containing longitude, latitude, time and solar zenith angles (SZA)
  - Simulate the Precessionary 90° (P90) orbit
  - Generate the 1:30PM and 10:30 AM Sun Synchronous (SS) orbit
  - Assume 100^km footprint (spatial resolution of CERES grid)
  - Assume 15 second (110 km) along ground track sampling
- The CERES dataset contains the nadir hourly radiances on a 1° by 1° latitude by longitude grid for 5 years
  - Sample the nadir radiance from the CERES dataset, every 15 seconds, from the region containing the ground track latitude and longitude
- Average all sampled SW and LW radiances into 10° zones for each of the dataset years

SW P90 Sampling Error

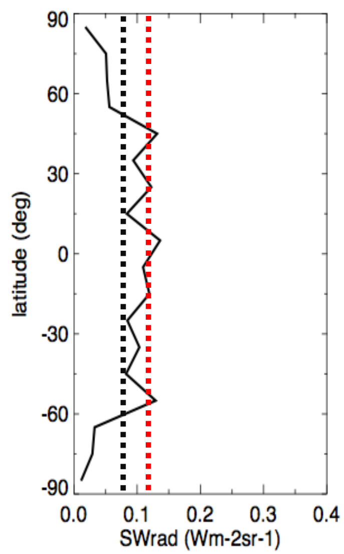
Natural variability anomaly



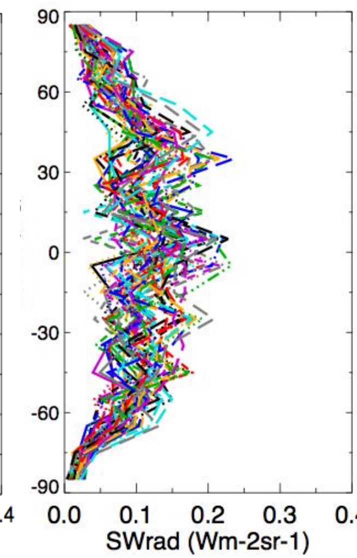
P90 observed variability anomaly



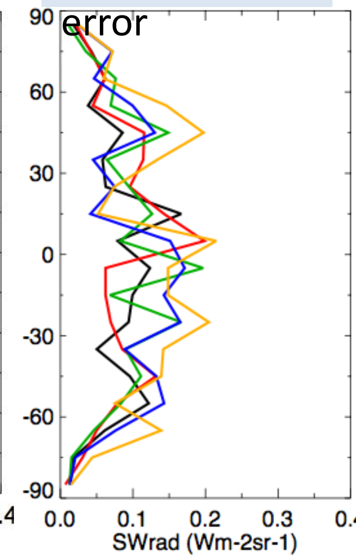
P90 sampling error



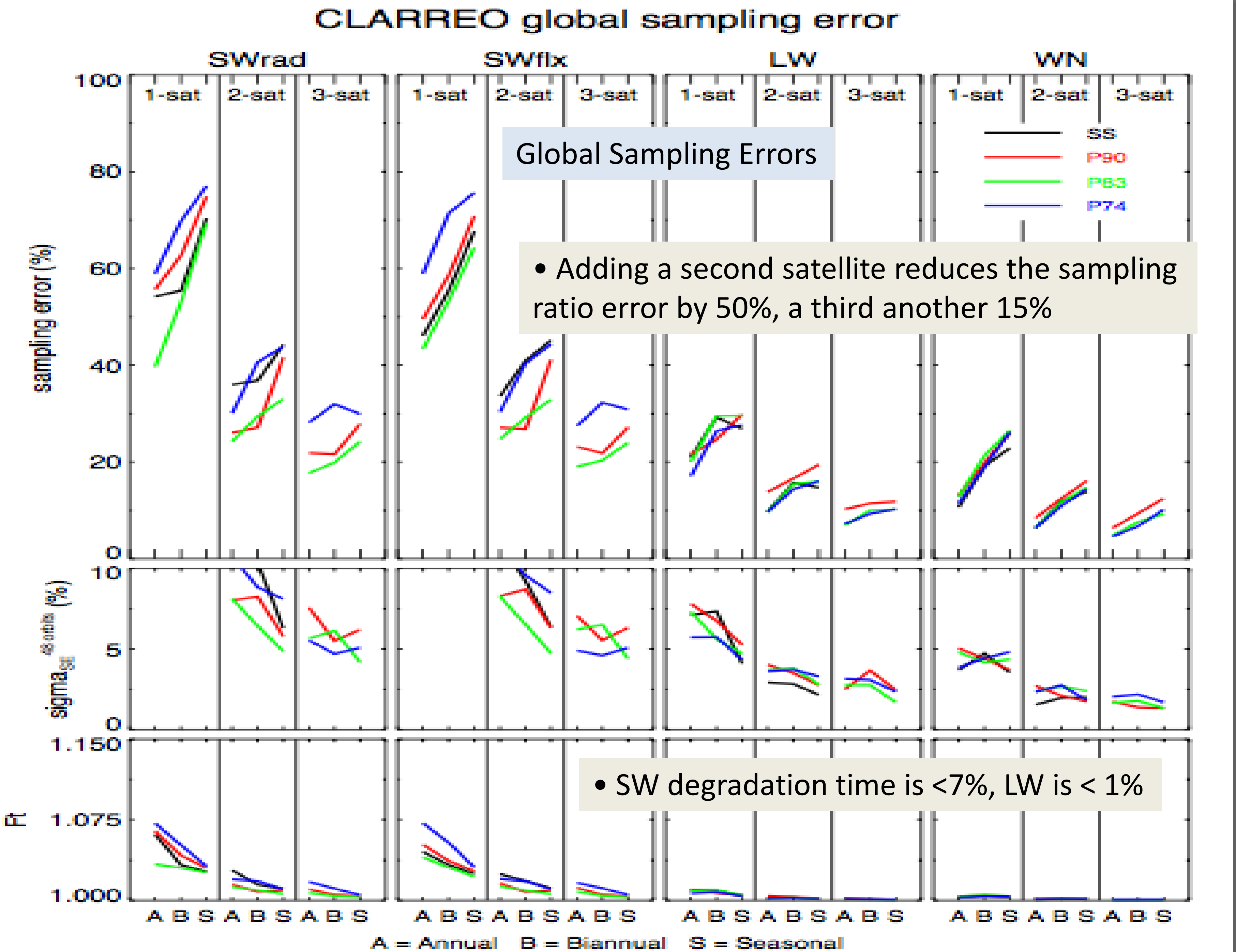
P90 48 orbit sampling errors



P90 min, 1/4,median, 3/4, max sampling error



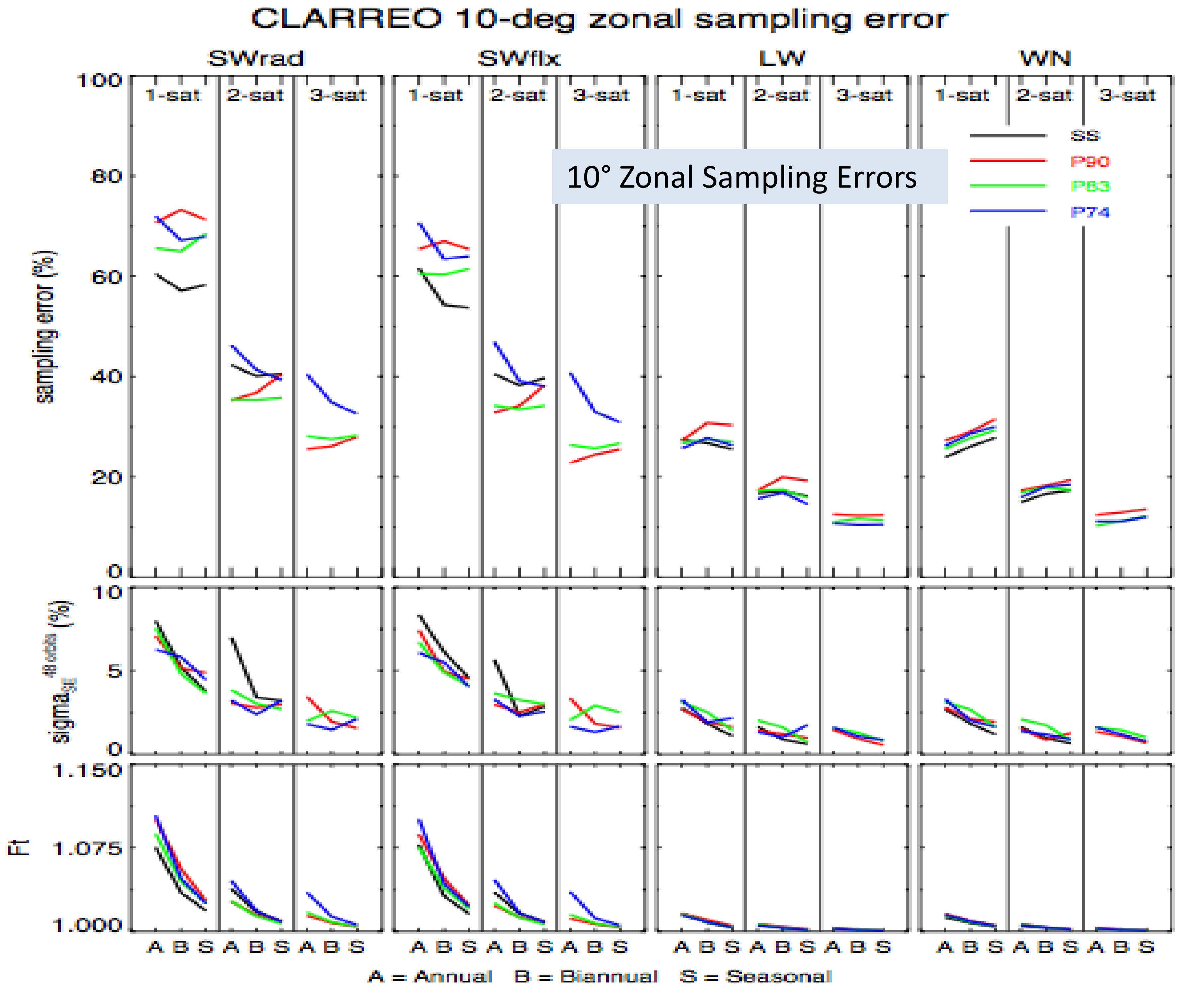
SW radiance (Wm-2sr-1)	Natural 1-sigma	Sampled RMS	Sampled (median) RMS (+1sigma)	Sampling (median) error ratio (%)	Sigma 48 orbits error (%)	Ft
Global	0.055	0.029	-	53	17	1.06
Zonal	0.192	0.101	0.135	70	7	1.10



Global Sampling Errors

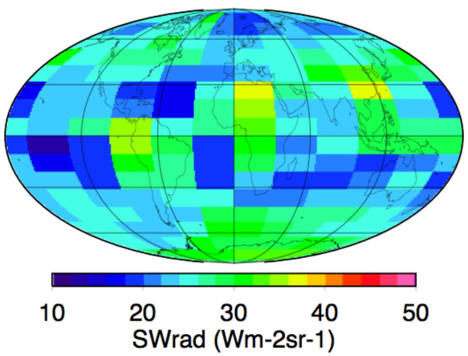
- Adding a second satellite reduces the sampling ratio error by 50%, a third another 15%

- SW degradation time is <7%, LW is < 1%

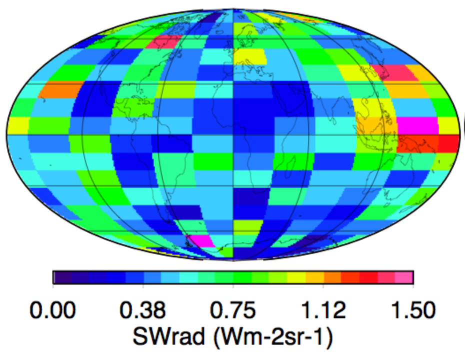

CLARREO 10-deg zonal sampling error
SWrad
SWflx
LW
WN
1-sat
2-sat
3-sat
SS
P90
P83
P74
10° Zonal Sampling Errors
sampling error (%)
$sigma_{SE}^{48\ orbits}$ (%)
Ft
100
80
60
40
20
0
10
5
1.150
1.075
1.000
A B S
A = Annual B = Biannual S = Seasonal

SW P90 Regional Sampling Error

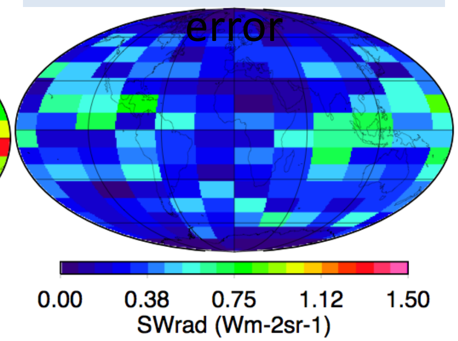
5-year SWrad mean



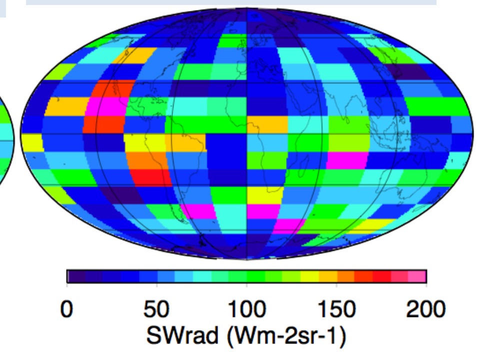
SWrad Natural variability anomaly



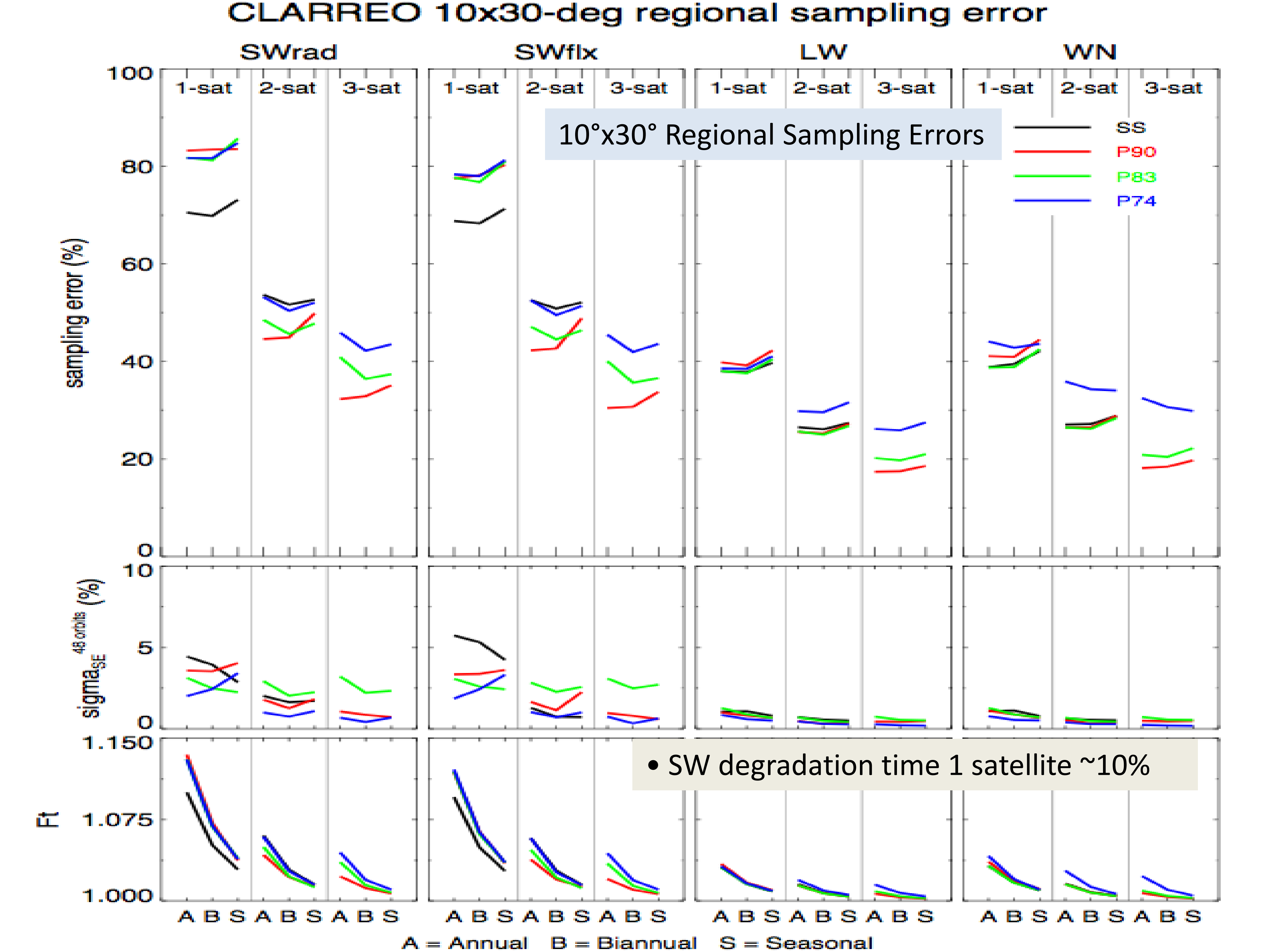
P90 median sampling RMS error



P90 sampling error ratio (%)

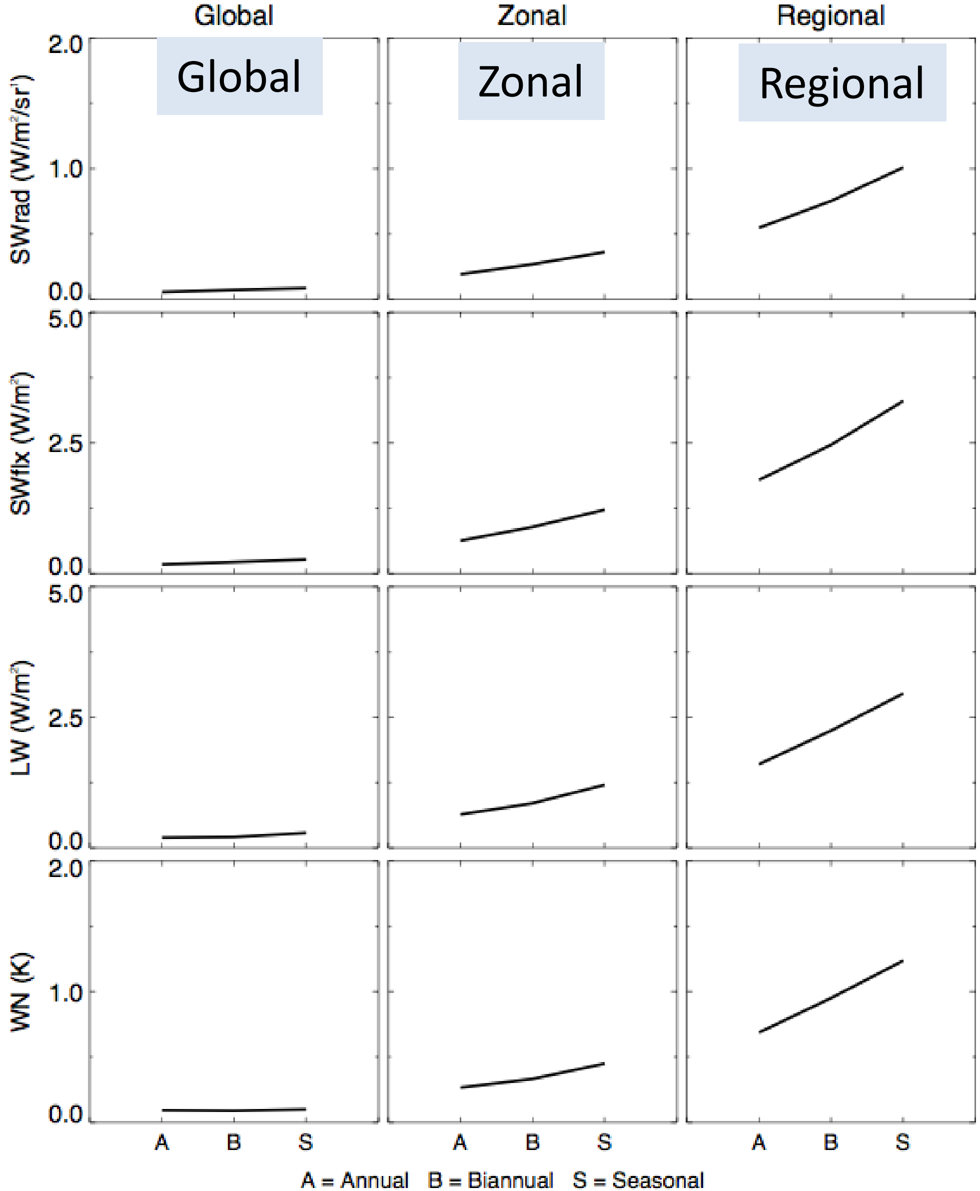


SW radiance (Wm-2sr-1)	Natural 1-sigma	Sampled RMS	Sampled (median) RMS(+1sigma)	Sampling (median) error ratio (%)	Sigma 48 orbits error (%)	Ft
Regional	0.546	0.317	0.454	83	~4	1.13



CLARREO 10x30-deg regional sampling error
SWrad
SWflx
LW
WN
1-sat
2-sat
3-sat
10°x30° Regional Sampling Errors
SS
P90
P83
P74
sampling error (%)
sigma_SE 48 orbits (%)
Ft
• SW degradation time 1 satellite ~10%
A B S A B S A B S
A = Annual B = Biannual S = Seasonal

Natural Variability Anomalies



- Smaller time steps have increased natural variability.
- This implies that detecting the same trend at the seasonal scale will take a lot longer than at the global scale.

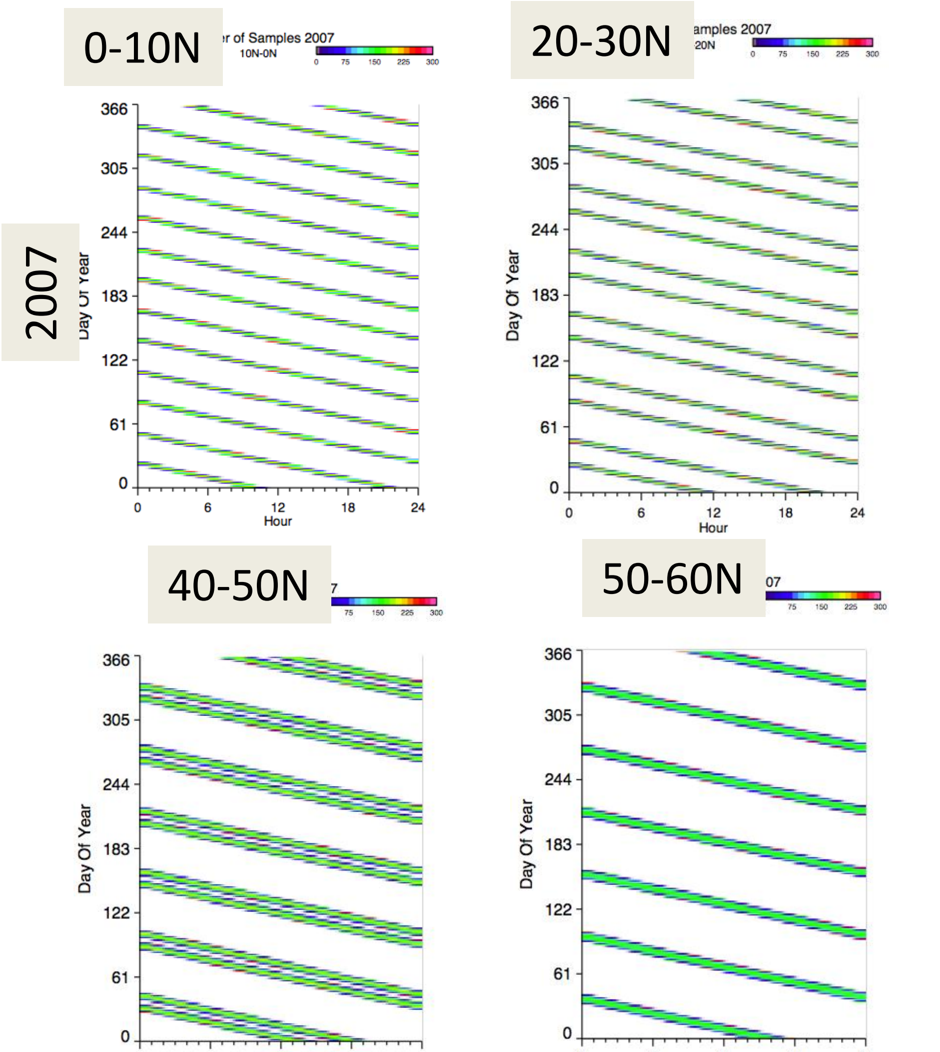
Benchmarking Conclusions

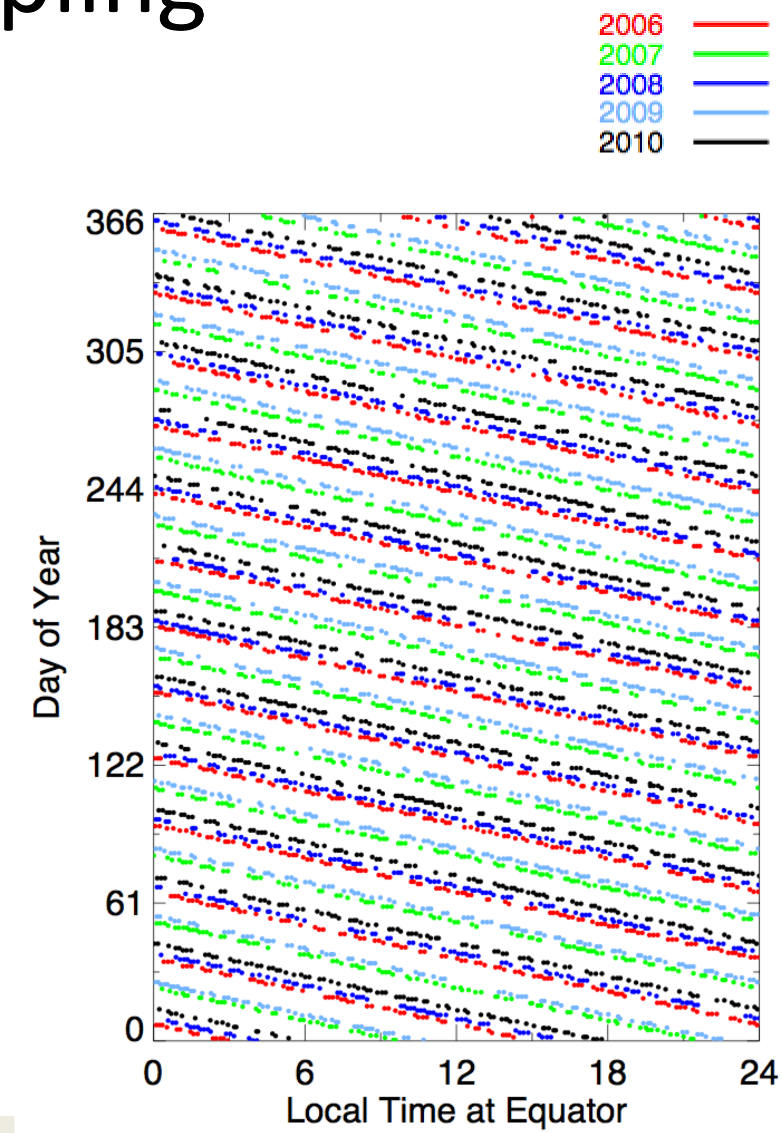
- Adding a second satellite reduces the sampling ratio error by 50%, a third another 15%
- The Zonal sampling error remains constant whether working with annual, semi-annual, or seasonal time scales
  - Natural variation increases with smaller time and spatial scales increasing time to detect trend
  - Sampling error ratio is constant with time scale
  - Ft decreases with higher time resolutions
- One P90 orbit provides sufficient LW sampling at the ~25% sampling error ratio and Ft =1.01, for zonal annual case
- One P90 orbit provides sufficient SW sampling at the ~70% sampling error ratio and Ft =1.10, for zonal annual case
  - Only half the measurements of LW
  - 1:30PM orbit SW sampling error is slightly lower than the P90 orbit
- Loss of sampling due to JPSS and MetOP inter-calibration ~1000/year @5 minute events (1% data loss) increased the sampling error by 5%
  - However inter-calibration is systematic, not randomly distributed

CLARREO defunded, seek other satellite options

- International Space Station
  - 51° precessing orbit, with altitude adjustments over time
  - 2006-2010 ground track data using 2001-2005 CERES data
  - ~12 diurnal cycles/year, non-repeatable annual orbits
- Iridium
  - 86° precessing orbit
  - 2006-2010 ground track data using 2001-2005 CERES data
  - Multiple orbits, offset ground track every 7.5° in longitude for 48 orbits
  - ~2.2 diurnal cycles/year, non-repeatable annual orbits

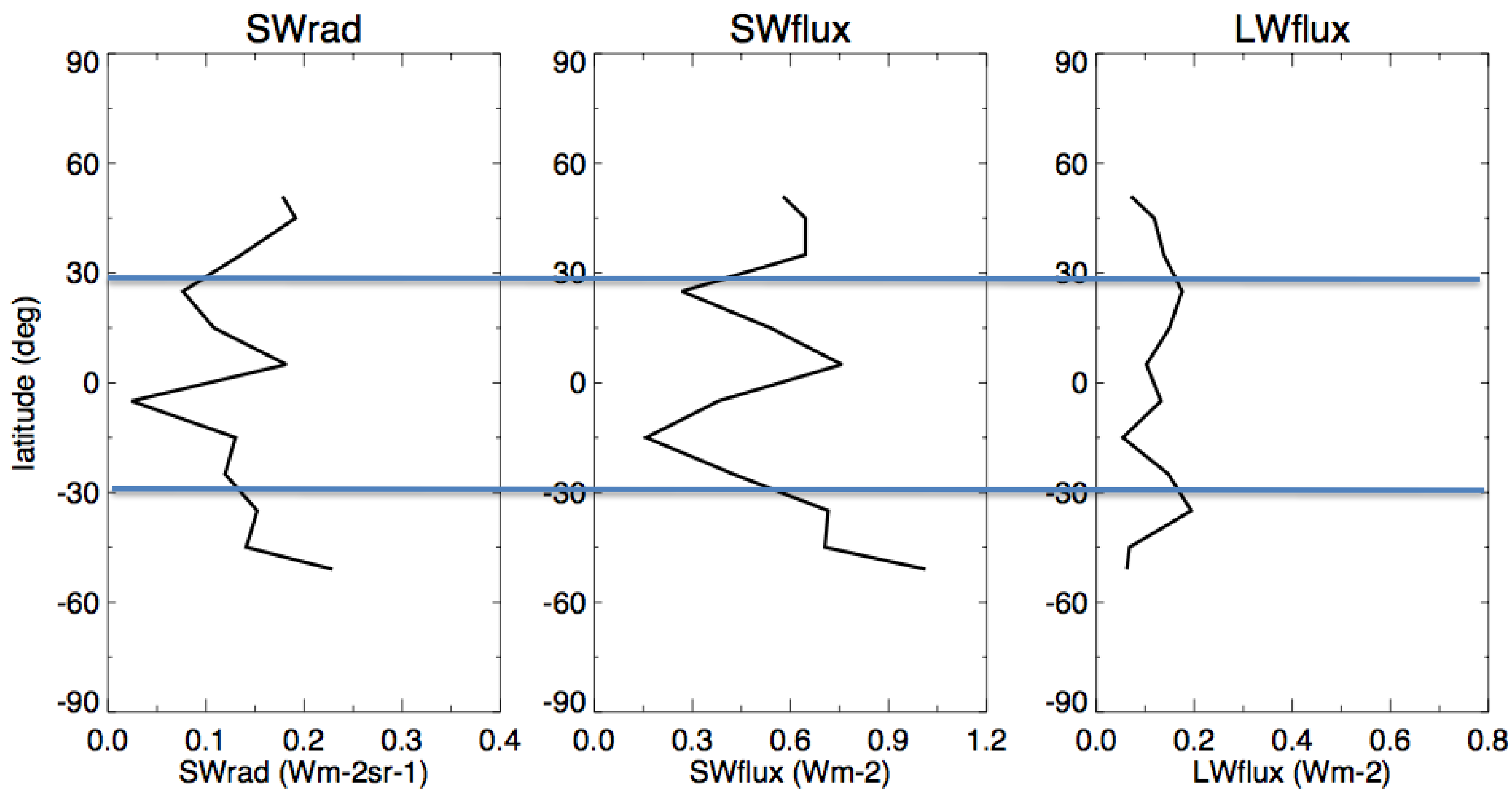
ISS sampling





- The annual sampling is not repeated
- These are very similar to some non-maintained orbit sampling studies last summer

ISS annual sampling



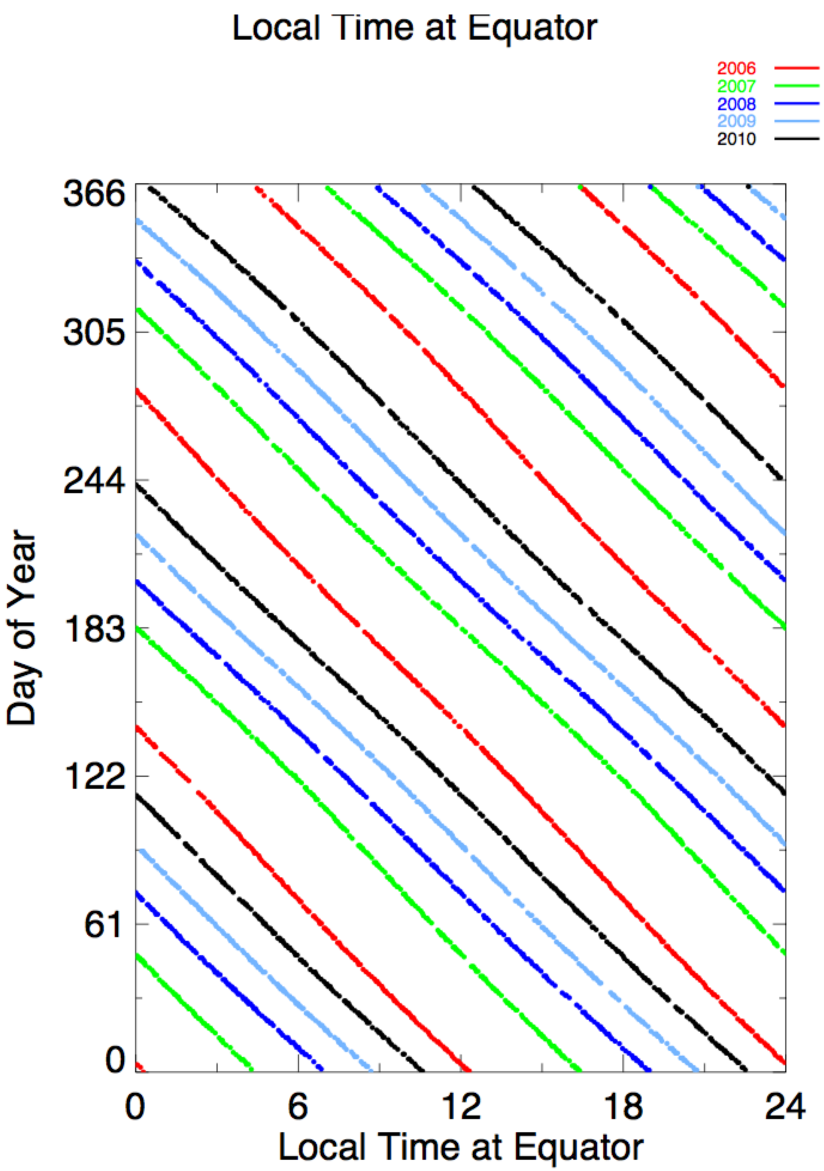
±60° latitude			
Global Sampling ratio=	1.09	2.09	0.22
Zonal	0.98	1.28	0.27
±30° latitude			
Global Sampling ratio=	0.37	1.17	0.10
Zonal	0.95	1.14	0.26

ISS Sampling Error/Natural Variability Table

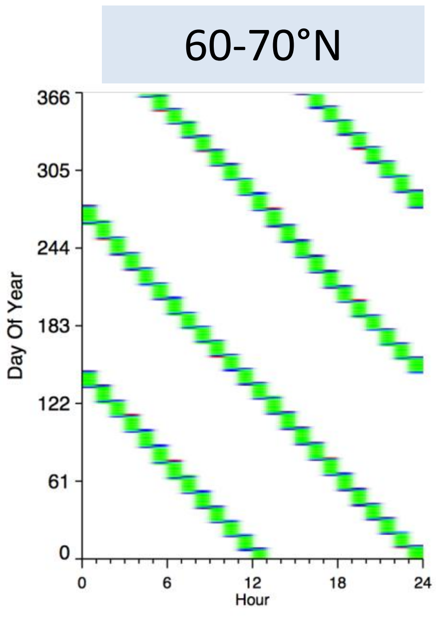
RMS(SAMP)/TRUTH (%)				
ZONAL 60	Swrad	SWflx	LWflx	WNflx
Annual	98	128	27	29
Semi	111	155	23	27
Quarter	120	142	43	59
GLOBAL 60	Swrad	SWflx	LWflx	WNflx
Annual	109	209	22	19
Semi	154	313	23	24
Quarter	129	213	35	45
ZONAL 30	Swrad	SWflx	LWflx	WNflx
Annual	95	114	26	27
Semi	80	120	20	23
Quarter	78	98	28	38
GLOBAL 30	Swrad	SWflx	LWflx	WNflx
Annual	37	117	10	11
Semi	45	120	14	13
Quarter	66	134	15	15

- The global sampling error is reduced by half sampling within the tropics
- The LW sampling error is unaffected by non-repeatable annual orbits

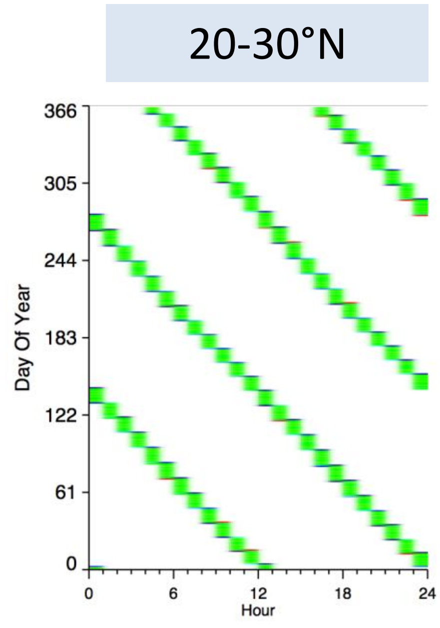
Iridium



Local Time at Equator
2006
2007
2008
2009
2010
366
305
244
183
122
61
0
Day of Year
0
6
12
18
24
Local Time at Equator

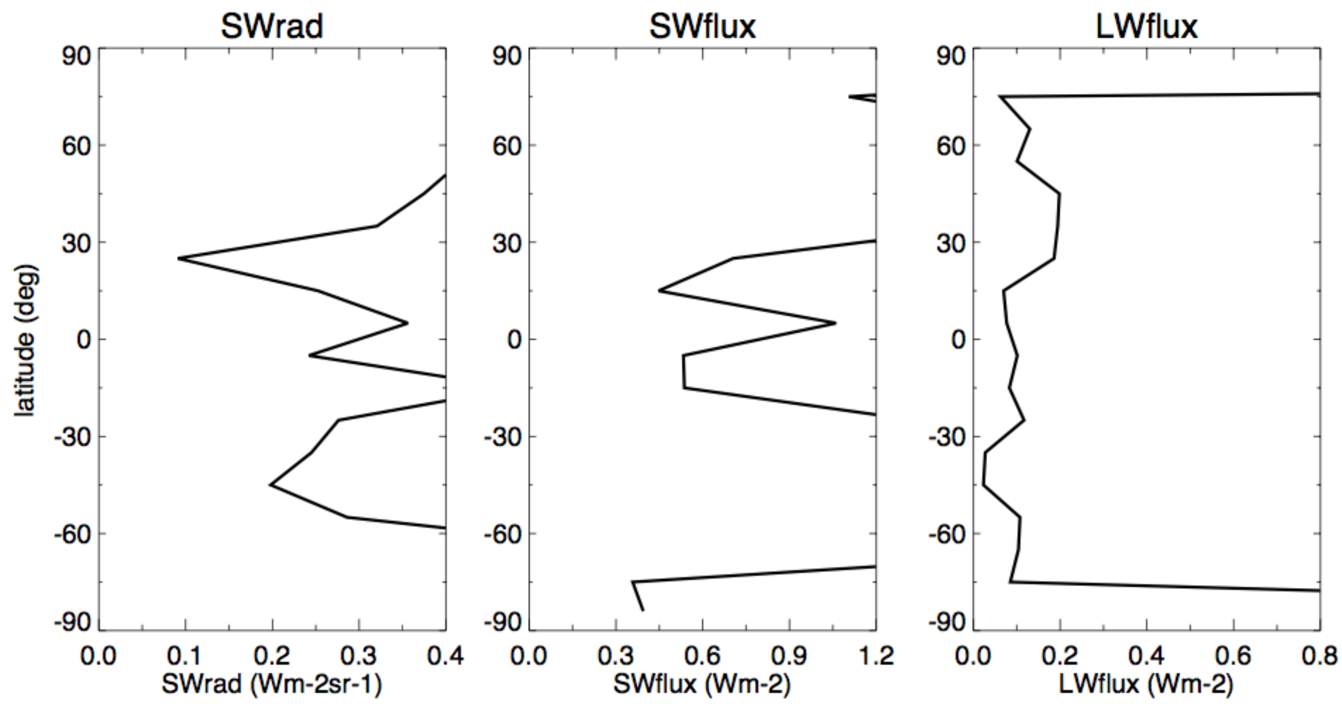


60-70°N
366
305
244
183
122
61
0
Day Of Year
0
6
12
18
24
Hour



20-30°N
366
305
244
183
122
61
0
Day Of Year
0
6
12
18
24
Hour

Iridium Annual Sampling



±80° latitude			
Global Sampling ratio=	2.74	2.79	0.36
Zonal	2.86	3.57	0.26

Iridium ISS Sampling Error/Natural Variability Table

ZONAL 80	Swrad	SWflx	LWflx	WNflx
Annual	286	357	26	26
Semi	246	371	33	37
Quarter	254	574	54	68
GLOBAL 80	Swrad	SWflx	LWflx	WNflx
Annual	274	279	36	21
Semi	215	865	75	58
Quarter	336	1712	131	136

- Zonal and Global SW sampling ratio ~250%, F_t~1.75
- Zonal and Global LW sampling ratio ~30%
- The LW/WN sampling error is unaffected by nonrepeatable annual orbits

Conclusions

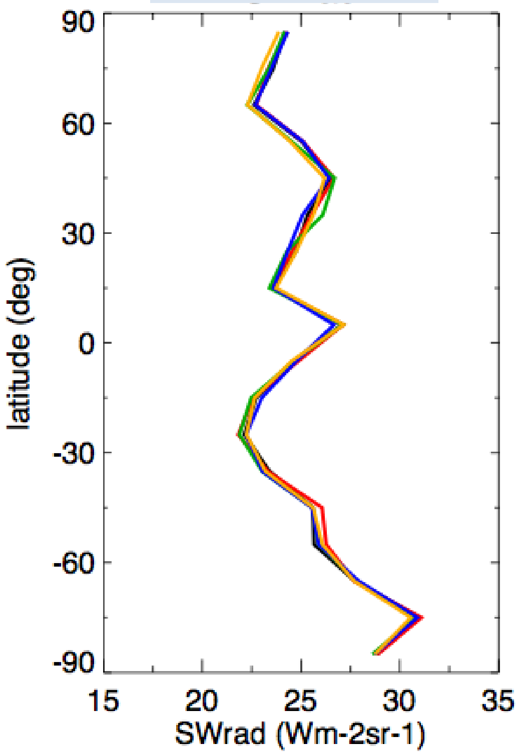
- ISS sampling, 51° precessing, ~12 diurnal cycle/year
  - SW zonal ±60° sampling ratio=95%, F_t=1.2
  - SW global ±30° sampling ratio=37%, F_t=1.02
  - LW zonal ±60° sampling ratio=26%, F_t=1.02
  - LW global ±30° sampling ratio=10%, F_t=1.01
- Iridium sampling, 86° precessing, ~2.2 diurnal cycle/year
  - SW zonal ±80° sampling ratio=250%, F_t=1.75
  - SW global ±80° sampling ratio=275%, F_t=1.80
  - LW zonal ±80° sampling ratio=36%, F_t=1.02
  - LW global ±80° sampling ratio=26%, F_t=1.02
- Are annual orbits needed?

Backup Slides

SW Natural variability (from CERES)

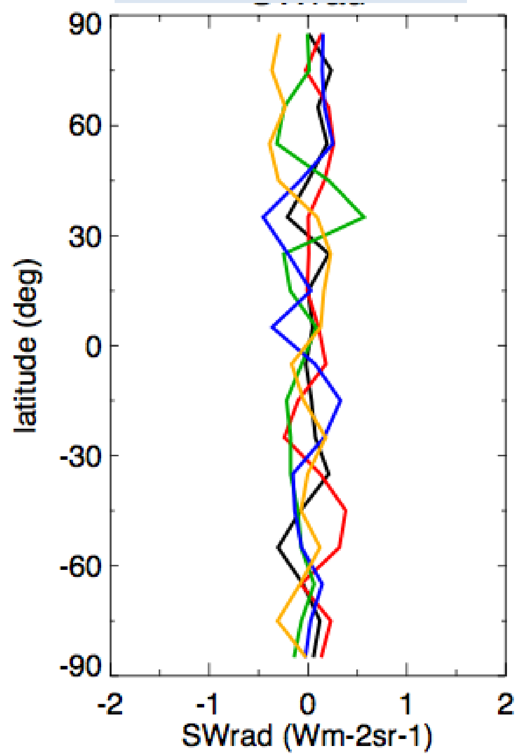
The annual mean is the average of all hourly radiances in the CERES dataset over the year in a 10° zone

Annual Means



2001	24.80
2002	24.85
2003	24.72
2004	24.74
2005	24.75
5-year Mean	24.77
Global 1-sigma	0.05

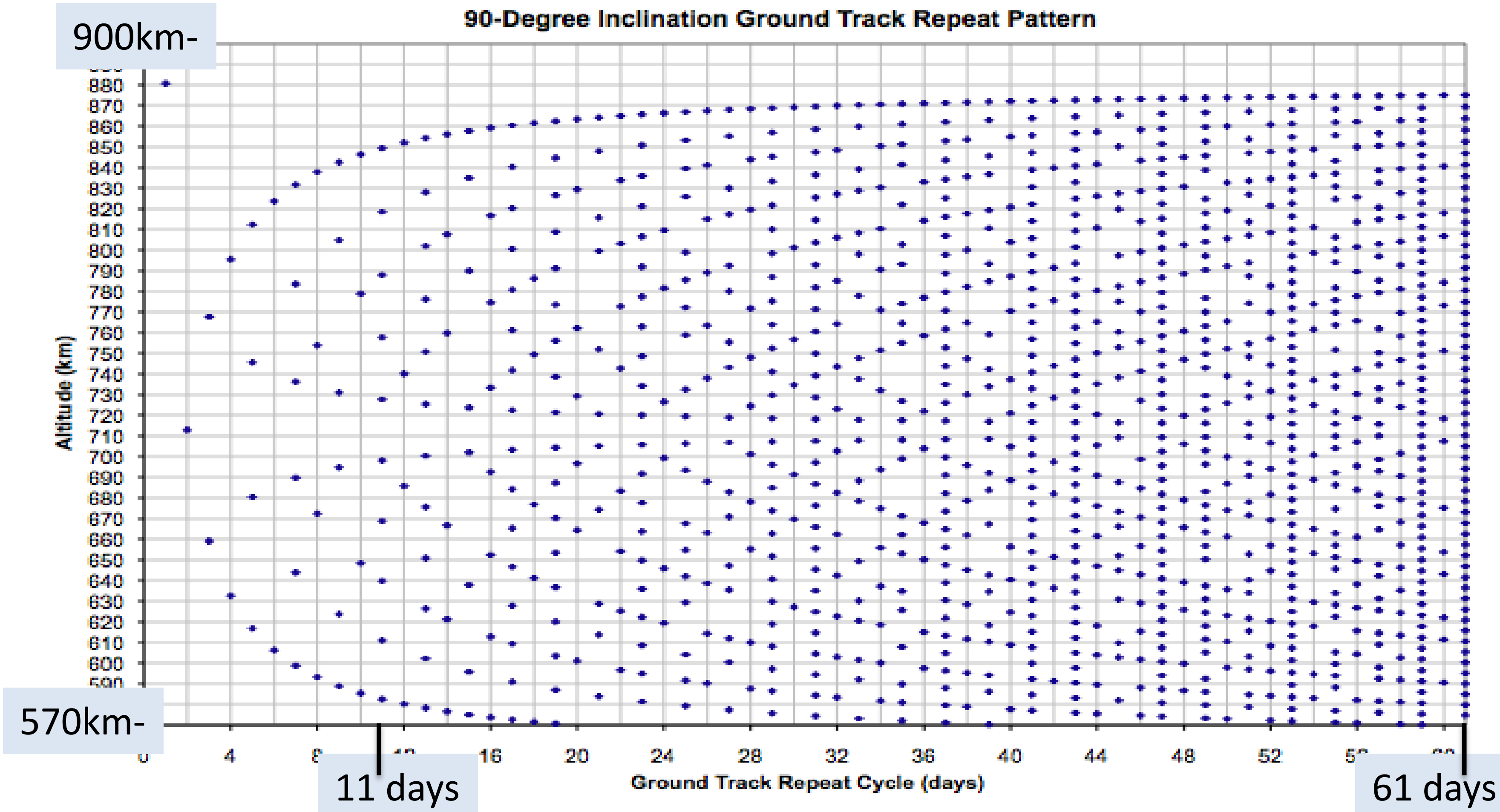
Annual Anomalies



2001	0.028
2002	0.080
2003	-0.059
2004	-0.029
2005	-0.020
5-year Mean	24.774
Global 1-sigma	0.055
Zonal 1-sigma	0.192

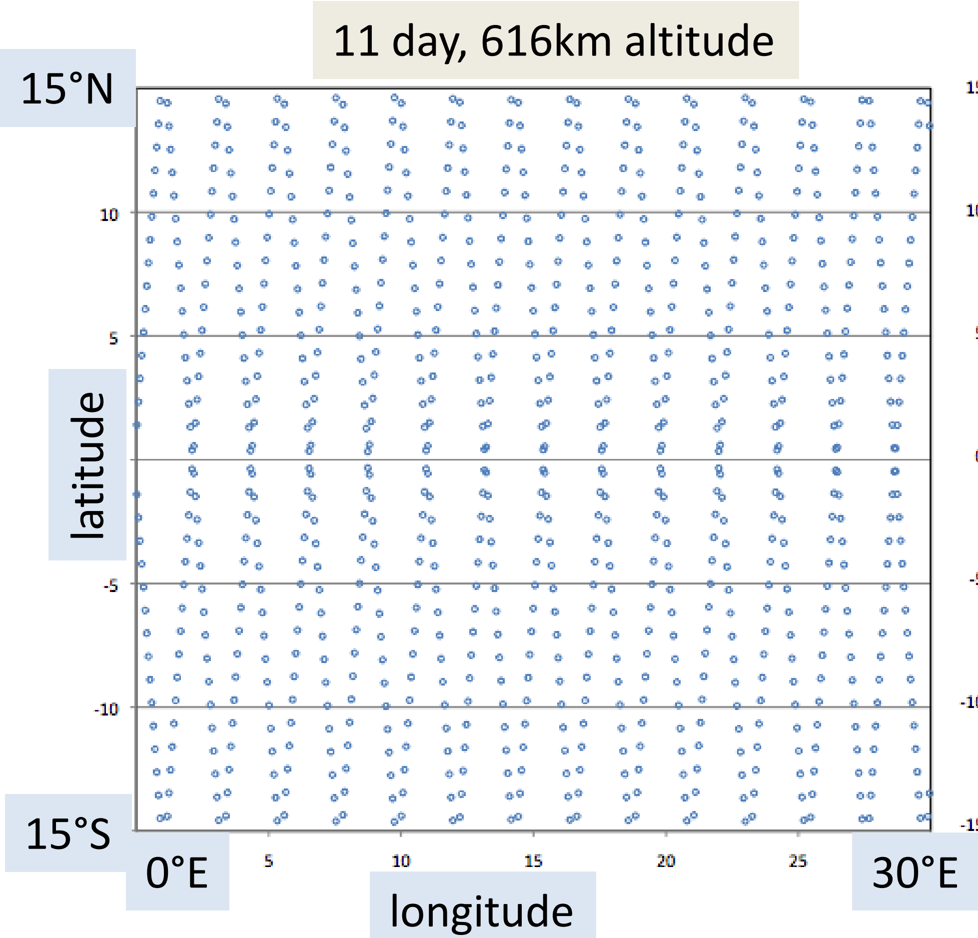
The annual anomaly is computed using the 5-year mean

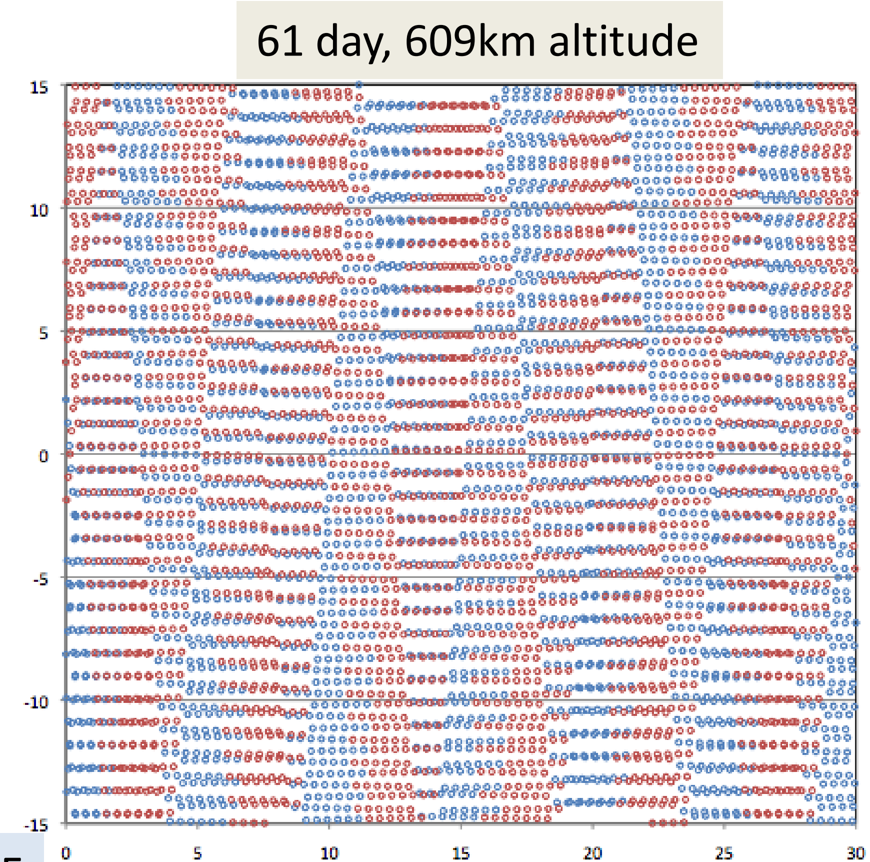
Altitude vs ground track repeat cycle for 90° orbit



- Ground track repeat cycle is very dependent on altitude
- Pick altitude with greatest repeat cycle
- This study uses 61 day repeat cycle

11 vs 61 day repeat cycle



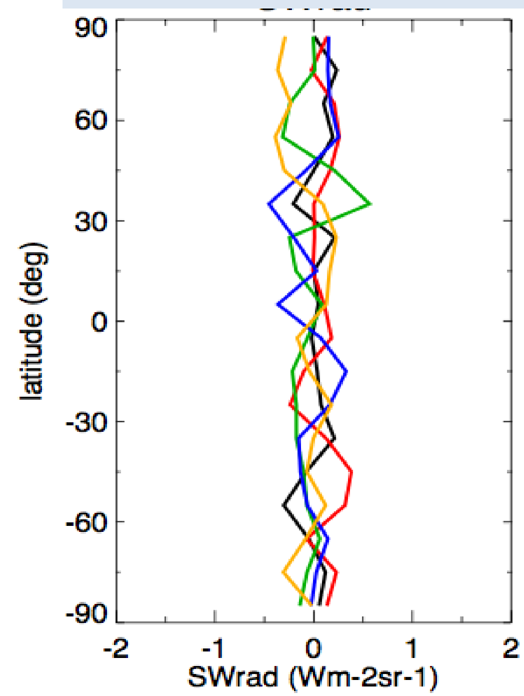


Blue first 30 days
Red second 30 days

- Each dot is 25km footprint, every 15 seconds
- Note the complete spatial sampling in the 61 day repeat cycle
- Use the preferred 609km altitude for P90

Sampling RMS Error

Natural Variability



2001	0.028
2002	0.080
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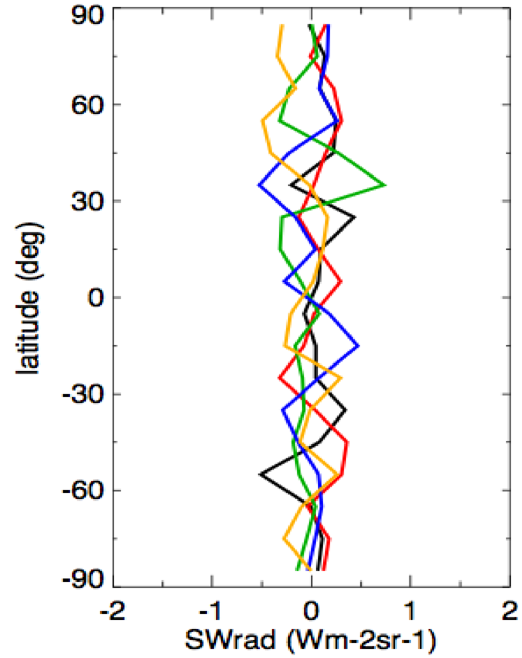
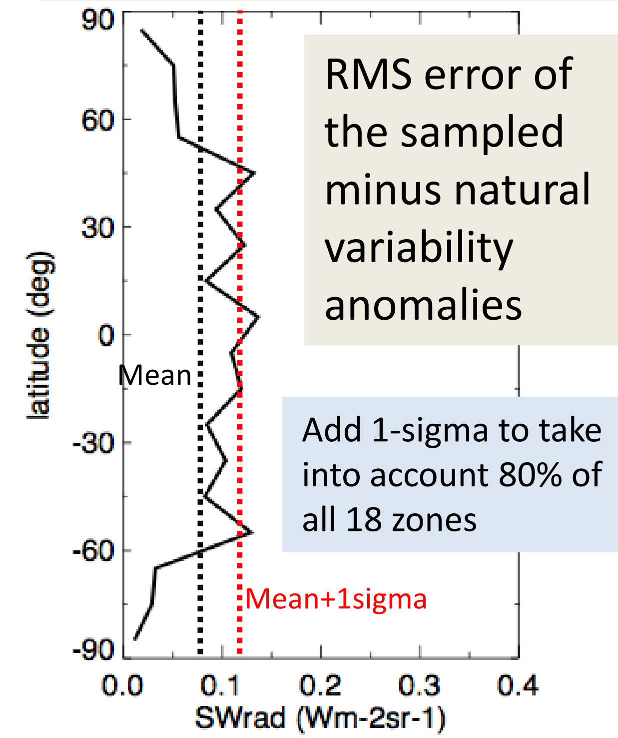
5-year Mean	24.774
Global 1-sigma	0.055
Zonal 1-sigma	0.192

Single 90° orbit sampling



	P90	Truth
2001	0.072	0.028
2002	0.069	0.080
2003	-0.052	-0.059
2004	-0.024	-0.029
2005	-0.066	-0.020
5-year Mean	24.838	24.774
Global 1-sigma	0.066	0.055
Zonal 1-sigma	0.225	0.192

Single 90° sampling RMS error

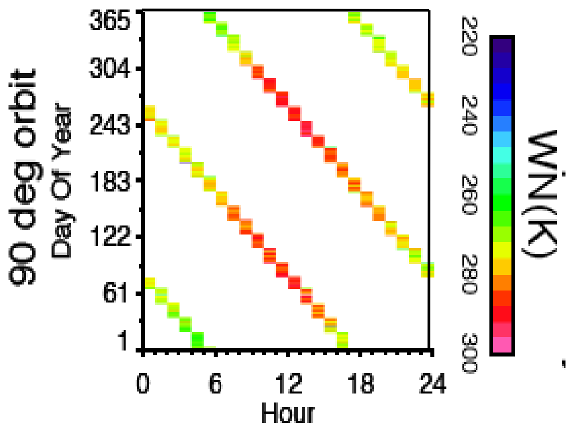


	P90 RMS	Truth 1-sigma	
Global	0.029	0.055	53%
Zonal **Mean**	0.080	0.192	42%
Zonal **Mean+1sigma**	0.116	0.192	60%

- The annual zonal anomaly sampling error for P90 is $(\sigma_{sampling}/\sigma_{var}) = 0.60$, $F_t = 1.10$
- For this case, assuming sampling error only, the time to detect trend is 10% greater than perfect observing system

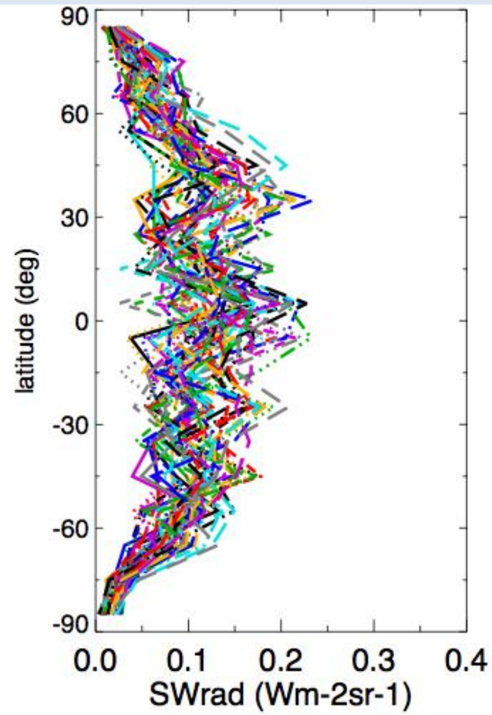
SW Sampling RMS Error

P90 sampling pattern for the 20°-30° zone of local hour vs day of year



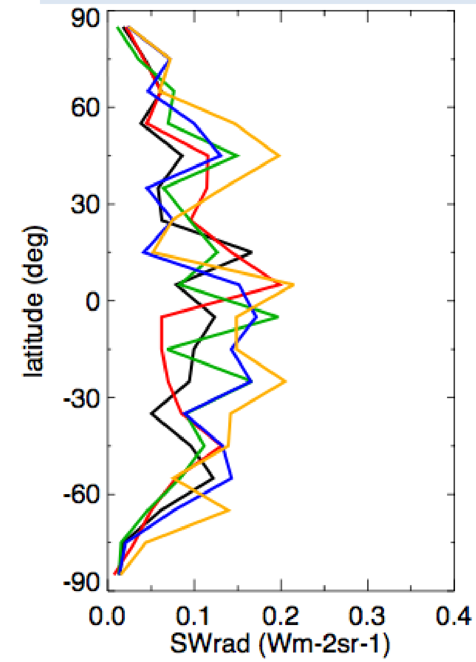
- By changing the start time of the orbit between 6 and 18 local time may have an impact on the sampling RMS error, since you are sampling the seasonal cycle at different times of day

90° sampling RMS errors for all 48 start time



- Use the median RMS error for statistics

All 48 start times, sorted from lowest to highest sampling error



Zonal RMS	P90	Truth
min	0.113	
1/4	0.127	
med	0.135	
3/4	0.144	
max	0.175	
Zonal 1-sigma		0.192

ZONAL RMS of Mean + 1sigma Sampling error ($\sigma_{sampling}/\sigma_{var}$) = 70%

10° Zonal Inter-annual sampling error

Annual	ZONAL					
	SWrad (Wm-2sr-1)		Swflux (Wm-2)		LW (Wm-2)	
	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t
σ_{var} [SS]	.197		.657		.637	
SS 13:30	59	1.07	58	1.07	26	1.01
SS 13:30+10:30	42	1.04	41	1.04	16	1.01
σ_{var} [P90]	.192		.628		.640*	
P90-1	70	1.10	65	1.09	25	1.01
P90-2	35	1.03	33	1.02	16	1.01
P90-3	26	1.01	23	1.01	12	1.00

* For LW 0.640Wm^{-2} = 0.194°K

- Adding a second satellite reduces the sampling ratio error by 50%, a third another 15%
- Single SS has a slightly reduced **SW** sampling error than on P90, but for two satellites, the P90 orbit is preferred
- All combinations of orbits have a very small F_t **LW** error <1.01 from perfect observing system

10° Zonal Bi-annual sampling error

Bi-annual	**ZONAL**					
	SWrad (Wm-2sr-1)		SWflux (Wm-2)		LW (Wm-2)	
	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t
σ_{var} [SS]	0.273		0.916		0.843	
SS 13:30	58	1.04	52	1.03	26	1.01
SS 13:30+10:30	40	1.02	40	1.02	17	1.00
σ_{var} [P90]	0.267		0.893		0.854	
P90-1	73	1.06	67	1.05	34	1.01
P90-2	40	1.02	37	1.01	22	1.01
P90-3	30	1.01	27	1.01	14	1.00

- Similar observations can be made for the Bi-annual case as with the annual except that the tau-sampling term is half of the annual case

10° Zonal Seasonal sampling error

Seasonal	ZONAL					
	SWrad (Wm-2sr-1)		SWflux (Wm-2)		LW (Wm-2)	
	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t
σ_{var} [SS]	0.371		1.260		1.201	
SS 13:30	66	1.02	59	1.02	24	1.00
SS 13:30+10:30	45	1.01	41	1.01	14	1.00
σ_{var} [P90]	0.361		1.221		1.208	
P90-1	75	1.03	67	1.02	29	1.00
P90-2	42	1.01	39	1.01	18	1.00
P90-3	28	1.00	25	1.00	11	1.00

- Similar observations can be made for the seasonal case as with the annual except that the tau-sampling term is a quarter of the annual case

10° x 30° Inter-annual sampling error

Annual	Regional					
	SWrad (Wm-2sr-1)		SWflux (Wm-2)		LW (Wm-2)	
	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t
σ_{var} [SS]	0.540		1.786		1.565	
SS 13:30	94	1.17	87	1.15	50	1.05
SS 13:30+10:30	75	1.11	63	1.08	31	1.02
σ_{var} [P90]	0.541		1.794		1.563	
P90-1	105	1.20	101	1.19	55	1.06
P90-2	56	1.07	52	1.06	32	1.02
P90-3	38	1.03	36	1.03	23	1.01

- regional errors are the mean + 1 sigma of 216 regions
- The annual regional resolution is on the cusp of single satellite **SW** sampling error

Single satellite sampling error

Time/Space	Regional					
	SWrad (Wm-2sr-1)			LW (Wm-2)		
	σ_{var} (Wm-2sr-1)	σ_s/σ_{var} (%)	F_t	σ_{var} (Wm-2)	σ_s/σ_{var} (%)	F_t
SS 13:30						
Annual Zonal	0.197	59	1.07	0.637	26	1.01
Bi-annual Zonal	0.273	58	1.04	0.843	26	1.01
Seasonal Zonal	0.371	66	1.02	1.201	24	1.00
Annual Regional	0.540	94	1.17	1.565	50	1.05
P90-single						
Annual Zonal	0.192	70	1.10	0.640*	25	1.01
Bi-annual Zonal	0.267	73	1.06	0.854	34	1.01
Seasonal Zonal	0.361	75	1.03	1.208	29	1.00
Annual Regional	0.541	105	1.20	1.563	55	1.06

* For LW 0.640Wm^{-2} = 0.194°K

- Note the increase in natural variability progressing to higher temporal and spatial resolutions
- The SW P90 zonal sampling error ratio remains fairly constant for temporal resolutions
- The SW P90 zonal F_t decreases with increasing temporal resolution
- The annual regional is on the cusp of single satellite sampling
- The SW sampling error ratio is ~2x > then LW, since SW is only available during daytime